

CONCEPTUAL GRAPH ANALYSIS: A TOOL FOR CURRICULUM DEVELOPMENT, INSTRUCTIONAL DESIGN, AND TRAINEE EVALUATION

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ABSTRACT

The knowledge base in a given domain has an inherent structure within it, corresponding to the interrelationships between concepts, propositions, images, etc. Written language often makes that structure obscure because of its linear format and frequent ambiguities. Graphs can be used to make the structure of knowledge explicit, and this allows for a variety of knowledge engineering procedures and analyses to be performed with or upon the graphs. Conceptual graph structures are a particular type of graph, consisting of nodes and labeled arcs, which can be used to represent both declarative and procedural knowledge. The graphs rely on a highly specific syntax developed by Art Graesser and colleagues over a period of ten years, and have been empirically validated in several domains. The conceptual graph syntax described in this paper is a modified version developed at the University of Idaho specifically for knowledge engineering and instructional design purposes. Conceptual graph structures can be used to represent a variety of types of knowledge including taxonomic knowledge, goal structures with arcs corresponding to if-then rules, spatial knowledge, and causal knowledge. The structures can be used to depict the content and structure of a *body of knowledge either for a particular individual or for a domain in general*. This representational capability supports a variety of instructional activities including curriculum development and analysis, instructional design and development of instructional materials, and trainee evaluation.

ABOUT THE AUTHORS

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BACKGROUND

Many of the activities involved in training program development require the analysis of large bodies of knowledge. Several researchers in instructional design have suggested the use of graphs or knowledge networks to organize and evaluate such bodies of knowledge (e.g., Fisher, Faletti, Patterson, Thornton, Lipson, & Spring, 1990; Nordstrom & Clayton, 1988; Novak & Gowin, 1984; Jonassen, Beissner, & Yaccli, 1993).

While this goal is worthwhile, efforts to use graphs for representing large bodies of knowledge in instructional design activities have been hampered by several problems. In the next section, we briefly review the more popular types of graphs, their use for instructional design and student evaluation, and the major drawbacks of efforts to date. In the remaining sections, we describe a graph method we are using in instructional design activities that alleviates these problems, some of our work to date, and the generic ways that the method can support training and instructional design.

Graph Types

Cognitive psychologists have suggested the use of networks to represent knowledge for over 20 years (e.g., Quillian, 1968). Most of these graphs have been a specific type knowledge, generically termed semantic networks. Semantic networks are graphs where nodes represent unitary concepts such as "bird," and the links represented

relationships between them. The relationships in such networks usually convey taxonomic or descriptive relationships, such as Is-A or Has Property (see example illustrated in Figure 1).

Researchers in education have recently increased the use of semantic networks to represent individual or domain knowledge. In particular, Novak and Gowin (1984) suggested the use of "concept maps" for showing the interrelationships between concepts. Concept maps consist of concept nodes that are interrelated by various types of relationships. These relationships are unconstrained, and are typically whatever verbs are used in the text being studied or analyzed. The terms concept map and semantic network can be and are often used interchangeably. However, concept maps sometimes show causal relationships while semantic networks are usually restricted to taxonomic types of relationships.

A different type of graph is often used to describe and test psychological or instructional theories. These graphs are termed causal networks or causal models. In causal networks, nodes represent either explicit or implicit variables (such as "motivation"), and the links are of one type only, A Causes B. Although Jonassen et al. (1993) suggest their more general use for depicting causal relationships in a domain knowledge structure, causal networks have not been commonly used representational media in instructional activities.

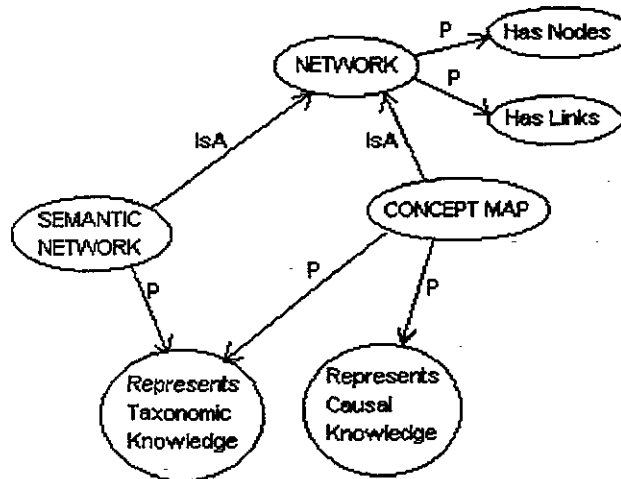


Figure 1. Semantic network showing taxonomic relationships. P denotes Has Property link.

Finally, Kieras (1988) has recently suggested the use of goal structures in performing task analysis. The goal structures have a specific format and syntax, known as GOMS, for Goal, Operators, Methods, and Selection Rules. These goal hierarchies are used to show the various means by which a person can operate some system to attain a higher order goal.

Instructional Uses of Graphs

Graphs such as semantic networks have been used for a variety of instructional design activities. Novak and Gowin (1984), and Jonassen et al. (1993) suggest using concept maps for planning entire curricula as well as more specific instructional activities. Nordstrom & Clayton (1988) have also suggested the use of concept maps to identify the interrelationships in children's literature and determine methods of teaching depending on individual learning styles.

Educational researchers are now arguing that concept maps can be useful instructional tools (Holley & Dansereau, 1984; Fisher et al., 1990). For example, Fisher and colleagues have students who are studying biology work individually or in groups to create networks of their knowledge as they acquire it. Ward (1988) proposes that construction of semantic maps helps learners build more complex knowledge structures and

better identify the interrelationship among ideas.

Holley and Dansereau (1984) suggest use of the following types of relationships in supporting student learning:

- X is an Instance Of Y
- X is a Property Of Y
- X is Similar To X
- X is Greater Than (or Less Than) Y
- X Occurs Before Y
- X Causes Y
- X is the Negation Of Y

Notice that most of these relationships are found in descriptive or taxonomic structures. That, is the concepts are used for definitions and descriptions of other concepts. Only the Occurs Before and Causes links provide a different type of knowledge, that of the interrelationships in a causal system. Such primarily taxonomic relationships and networks are commonly used in academic domains. One can speculate that this is because most of the information that is taught is general taxonomic knowledge.

Finally, some researchers suggest having the students graph their own semantic networks. These networks can then be used by the instructor to evaluate the accuracy of student knowledge (Fisher et al, 1990, Moreira, 1979).

Drawbacks and Difficulties

There are three major drawbacks to the graphical representation methods developed and used to date.

(1) Restrictive representation of knowledge types. First, the graph syntaxes used to date are too restrictive. That is, some graph types such as concept maps are useful for representing concepts and their taxonomic relationships. Others, such as GOMS, are useful for representing goal hierarchies. There is no graphing method used in instructional design that is capable of representing a wide variety of knowledge types, such as spatial knowledge, causal structures, goal hierarchies, images, if-then rules, etc. This type of representation is critical in real-world training because of the applied nature of the knowledge being taught.

(2) Lack of standardized syntax. A second problem with some representational methods is that there is no syntax or "language" per se. For example, concept maps rely on the use of verbs from text or whatever types of links that the researcher finds appropriate (reference). This lack of standardization creates several problems such as making it more difficult for two or more researchers to work together (no common language), difficult to compare different person's graphs on the same topic, and a proliferation of different types of links, many of which are more similar than different. This results in graphs that are poorly organized and "diffuse."

An exception to this problem is the syntax used in the GOMS method; this syntax is quite parsimonious.

(3) Lack of knowledge base management tools. Finally, until recently there have been no reasonable ways to manage the knowledge base if one moves beyond several dozen graph nodes. Graphs have simply been more difficult to manage because they were not amenable to manipulation on a computer.

In the previous six years, we have been using a particular graph syntax that overcomes the first two problems. More recently, we have been using a software program on a personal

computer to store and analyze the graphs that is able to manage even very large networks. The graph syntax and the computer software are described in the next two sections.

CONCEPTUAL GRAPH STRUCTURES: THE REPRESENTATIONAL MEDIUM

Conceptual graph structures (CGSs) are a type of graph consisting of nodes linked by labeled, directional arcs.¹ Figure 2 shows a very small and incomplete example of a CGS, in this case depicting only taxonomic knowledge. It can be seen that each node contains specific content information and also a label specifying the type of knowledge. The information can be a unitary concept, or a statement. Statements are one of five node types:

Event
State
Style
Goal
Goal/Action

Any node in a CGS is labeled with one of these categories, either implicitly or explicitly (as in Figure 2). However, there are certain times when a researcher may want to leave the node labels out of the graphs (for example, when using them to structure interviews with subject matter experts).

As noted earlier, CGSs may contain different types of knowledge, such as taxonomic, goal hierarchies, causal structures, etc. These different types of knowledge are revealed by the types of arcs relating different nodes. For that reason, the arcs in CGSs are best described in reference to the type of knowledge they convey.

Table 1 shows the four major types of knowledge or substructures found in CGSs. It can be seen that taxonomic structures tend to predominantly consist of Is-A, Has Property (opposite of Property OF), and Has Instance arcs.

¹Conceptual graph structures were originally developed by Art Graesser (Graesser & Clark, 1985); the syntax described in this article is that presented in Gordon & Gill, 1992.

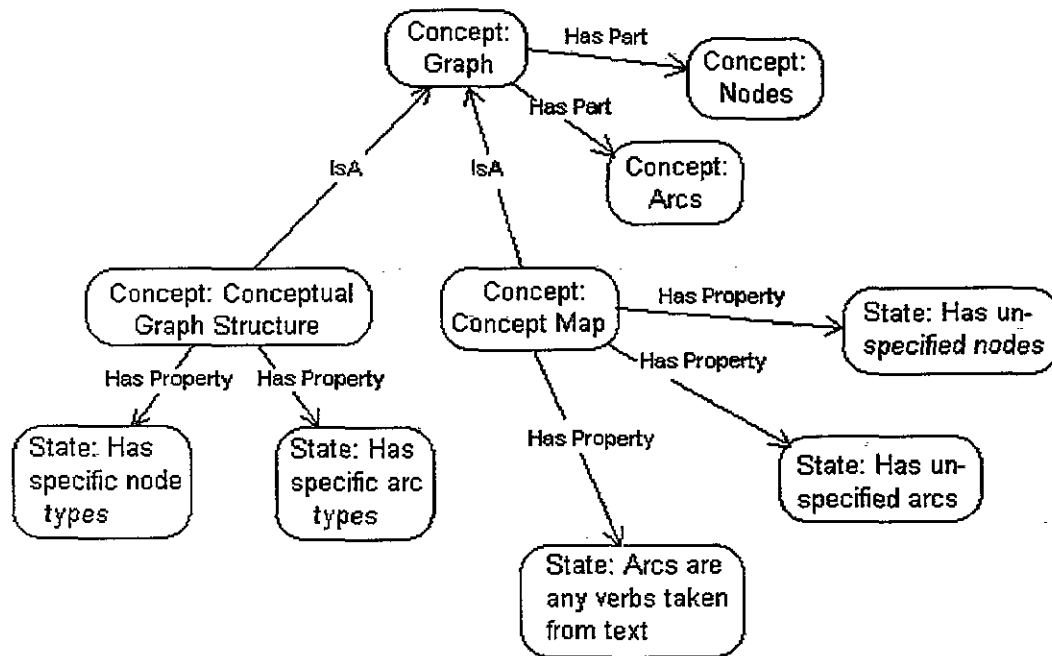


Figure 2. Conceptual graph structure showing taxonomic relationships.

Table 1. Conceptual graph substructures and arcs commonly used within the substructures.

TAXONOMIC STRUCTURES: Specify the relationships between superordinate and subordinate concepts (e.g., Apple Is-A Fruit).

Is-A
Has Property
Has Instance
Has Part
Refers-to
And/Or

SPATIAL STRUCTURES: Contain knowledge delineating the spatial layout of regions and objects in regions.

Above/Below
Left-of/Right-of
Behind
etc.

CAUSAL NETWORKS: Contain knowledge about causally driven state and event chains.

Has Consequence
Manner
Before/During/After
And/Or

GOAL HIERARCHIES: Specify goals, cognitive activities, and behavior procedures for accomplishing goals.

Means
Initiates
Before/During/After
Manner
Has Consequence
And/Or

It can also be seen that goal hierarchies predominantly consist of three types of links:

Means: A Goal/Action (goal or activity) is carried out by means of some activity

Initiates: A state or event initiates a particular goal/action

Has Consequence: A goal/action has some consequence

Causal structures contain mostly Has Consequence arcs (essentially the same as "Causes").

Figure 3 shows the graph for a small amount of information relevant to use of a VCR. It can be seen that several different types of knowledge or substructures can be contained or joined within one large graph.

Advantages of Using the Conceptual Graph Structure Syntax

Use of the conceptual graph structure syntax has several advantages over other graphing methods:

(1) Empirical support. The graph syntax and its use has received a wide variety of empirical support. For example: The conceptual graph

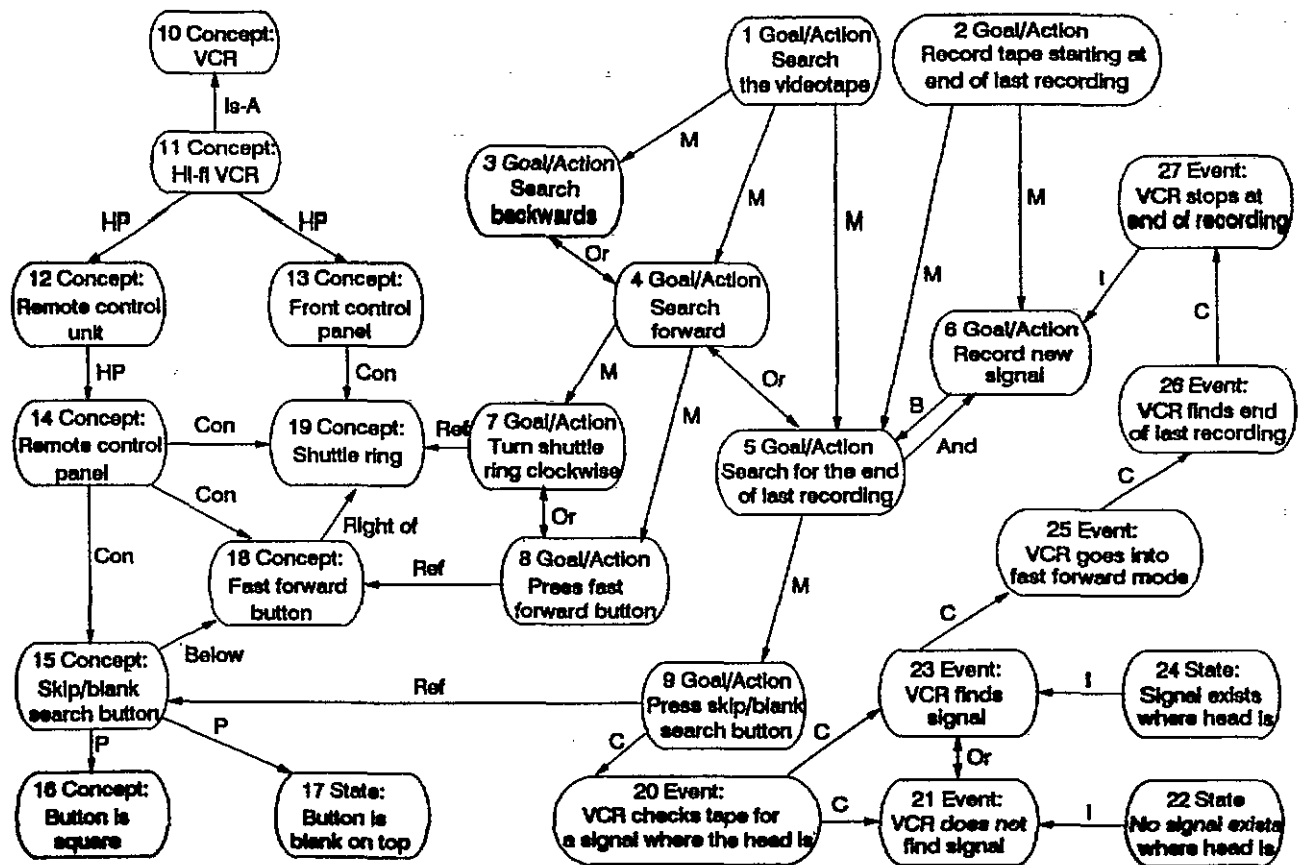


Figure 3. Conceptual graph structure for VCR with four types of substructure. Arc labels are: C: Consequence, Cont: Contains, HP: Has Part, I: Initiates, M: Means (by means of), and P: Has Property.

structure syntax itself has been shown to have high validity (Graesser & Franklin, 1990); the content and structure of individual's conceptual graph structures has been shown to predict subsequent problem solving (Gordon & Gill, 1989); and analysis of conceptual graph structures has been shown to increase the effectiveness of instructional text (Gordon, Schmierer, & Gill, in press).²

(2) Domain general. The graph syntax has successfully been used to represent knowledge in literally dozens of domains, ranging from narrative fairy tale stories to engineering mechanics (physics), forest stand prescription, use of VCRs and other mechanical systems, and procedures such as following recipes. This means that once a researcher or instructional designer learns the graph syntax (similar to learning any other language), that syntax can be reliably applied to new applications.

(3) Integrates different types of knowledge. Unlike other syntaxes such as GOMS or concept maps, the syntax can be used to represent and integrate all major types of knowledge including general taxonomic knowledge, goal structures, episodic knowledge, and visual images.

(4) Shorthand notation system. The graphs provide a useful shorthand for interviews, and a visual means to see interrelationships among concepts.

(5) Standardized syntax supports a systematic knowledge engineering methodology. The standardized node and arc syntax yielded and supports a method for knowledge acquisition, termed question probes (described below).

MANAGING THE GRAPHS ON A COMPUTER

Until recently, graphs of any size have been cumbersome to develop and manage. There are now several programs available for use on a personal computer to support this process. For most of our graph work, we are now using a special revision of a software product developed by the SemNet Research Group based in San Diego. The basic software is

called "SemNet," runs on a Macintosh computer, and is available by writing to Kathleen Fisher at San Diego State University. The revised version for developing conceptual graph structures is known as "SemNet Wide." This is because the software was modified so that nodes could accommodate the longer text strings needed in some conceptual graph structure nodes.

The SemNet and SemNet Wide software supports quick and efficient development of graphs. Most people are able to develop graphs with the software with little to no use of support documents (truly a feat in this day and age). The graphs show a node in the center, surrounded by all nodes related by one link. Any of these surrounding nodes can be clicked, at which time that node becomes the center node on the screen. The nets can be traversed in this manner, or more quick "go to" commands are also available. The nets can be viewed in a variety of list formats, and selected parts can be viewed. The software can also provide helpful information such as the number of associations emanating from a given node (one measure of node "centrality").

CONCEPTUAL GRAPH ANALYSIS

Knowledge Acquisition

Development of conceptual graphs (CGSs) can be accomplished in a number of ways. In previous work, we have suggested a complementary set of knowledge acquisition methods for development of graphs (see Gordon et al., this conference, Gordon et al., In press; Gordon & Gill, 1992). These include Document Analysis, Interviews structured with Question Probes, Observation, and Rational Analysis. Document analysis is usually used for initializing the graphs. It consists of translating contents of relevant documents into conceptual graph form. A second way of initializing a graph is to ask a subject matter expert to briefly describe the domain or task of interest (Gordon & Gill, 1992).

Once the graphs have been initialized, they must be expanded and clarified. The most effective method for doing this is to use question probes with one or more subject matter experts (Gordon & Gill, 1992). Alternatively, if an expert is developing the

²This will be elaborated in a section to follow.

graph, the question probes can be implicitly asked of oneself.

Question probes are generic questions that are asked for each node on a graph. Each node type (e.g., concept) has certain types of questions. For example, an event node would result in questions regarding that event such as:

What happens before _____?

What happens after _____?

What are the consequences of
_____ occurring?

Why does _____ occur?

Answers to the probes yield material to be added to the graph.

For procedural knowledge that is not easily obtained through interviews, direct observation can be used. Usually, an expert is observed and perhaps videotaped. Information such as initiating circumstances is identified and added to the graphs at appropriate points.

Finally, the graphs are evaluated using what might be termed "rational analysis." One main purpose for such an analysis is to identify any additional methods for accomplishing a task, or examples or concepts, etc. that should be included. For example, an expert may not have developed the optimal method for operating a system under all circumstances. An evaluation of the system itself might yield better goal hierarchies than those observed in actual performance.

Previous Applications of CGSS

We have used CGSSs for several activities related to instructional design. First, the graphs have been used in several projects to perform cognitive task analysis (Gordon, *In press*). This results in a graphical representation of the knowledge that is to be contained in an instructional program.

Second, we have used the method to improve instructional text. For example, we graphed a portion of text from a major textbook in engineering mechanics. Subject matter experts were given question probes and the graph was "engineered" on the basis of answers to the probes. A new text based on this engineering process

resulted in greatly improved problem solving by students (Gordon et al., *in press*). We have also used conceptual graphs to map out learner knowledge structures in detail. These individual graphs predicted problem solving with a high degree of accuracy (Gordon & Gill, 1989). Finally, we are currently involved in development of an intelligent tutoring system based upon a task analysis using the conceptual graph analysis methodology (see Gordon et al., this conference).

GENERAL APPLICATIONS OF CONCEPTUAL GRAPH ANALYSIS

The purpose of this paper is to suggest the means by which conceptual graph analysis can be used to support a variety of instructional activities. In this section, we will briefly describe some ways in which this can be accomplished.

Curriculum Design

To determine the courses and course content needed to successfully cover a given domain, it is usually necessary to analyze a number of relevant documents and hold discussions with numerous subject matter experts. The resultant body of knowledge must somehow be organized, evaluated, and divided into courses and topics. Conceptual graph structures can be used for this purpose.

Several general approaches are possible. First, one might assign one individual to be responsible for creating a network using SemNet or some other appropriate program. This person could act as knowledge engineer and use interviews or questionnaires with experts. Alternatively, one could have several experts individually develop graphs and then merge the graphs into one. Finally, a group of experts could work together as a team (with a projection system) to develop a graph.

Normally, one would start by "free associating" with respect to the topics and skills needed for the curriculum plan under consideration. For example, if we were developing the curriculum for a Ph.D. in Human Factors, we would first obtain information relevant to any accreditation and licensure policies from all appropriate societies. We would use that information and

our own ideas to list all of the knowledge and skills necessary for practice in the human factors profession. These "nodes" could then be interrelated in a number of ways in the graph. The most obvious way is a topical hierarchy, with general topics subsuming more specific topics. Arcs used for this purpose could be Is-A arcs, or more specific arcs could be used such as Has Subtopic.

However, it is also a good idea to go through a look for other types of relationships to develop a richer network. For example, certain skills might be prerequisite for a number of advanced tasks. One can connect prerequisite skills to their goal/action nodes by Has Prerequisite arcs. By linking all of these prerequisite skills into goal hierarchies, a count can be taken indicating the "importance" of such lower level skills. This count can become the basis of a priority ranking for determination of remedial needs. SemNet can automatically provide such information.

Once the content has been defined and interrelated, the organization of the nodes can be evaluated and divided into coherent courses and topical outlines. The graphs generally fall into clusters of topics. SemNet gives a measure of "embeddedness" that can be used by the researchers to identify such clusters.

Instructional Design and Materials Development

Each section of a graph that pertains to one course or course section can become the basis for instructional design activities. For each topic, an instructor can add nodes describing instances or examples (Has Instance), analogies (Is Similar to), and learning activities (Means or Taught By Means of). The content material itself can be developed in detail and then converted into text, tutorials, or hypertext (Gordon, in press).

Trainee Evaluation

It is often advisable to evaluate the factual and procedural knowledge acquired by trainees, especially if there are critical consequences of errors in task performance. Identifying the structural knowledge of trainees is a good method for determining whether they have sufficient knowledge for task performance.

Conceptual graphs have been shown to be highly sensitive measures of subjects' conceptual and procedural knowledge (Gill, Gordon, Moore and Barbera, 1988; Gordon & Gill, 1989). Question probes (Gordon & Gill, 1992) can be administered to trainees at appropriate times after learning activities. By evaluating how trainees interrelate concepts and procedures, one can determine exactly where there are gaps or misconceptions in the knowledge base (see Gordon & Gill, 1989 for a detailed description of methods for evaluating learner knowledge).

SUMMARY

The conceptual graph structure syntax can be applied to different domains with no or very few additions to the syntax. It can be used for a variety of instructional design activities, including curriculum development and analysis, and instructional design activities such as cognitive task analysis and development of instructional materials. It can also be used in conjunction with question probes to evaluate student understanding of complex topics and procedures, and to identify gaps and misconceptions in a student's knowledge base.

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